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STERL

RESOURCE HANDBOOK

HUNTINGTON TWO COMPUTER PROJECT

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RESOURCE HANDBOOK

STERL

Table of Contents

I. Background Information 1

Methods of Control 1

Pesticides 3

Sterile Male Technique 7

II. The *STERL* Model 10

III. Program Listing 15

IV. Additional Sample Runs 20

V. List of References 26

I. BACKGROUND INFORMATION

METHODS OF CONTROL

A pest is, by definition, any plant or animal that is annoying or destructive to either man, his crops, his livestock, or his property, etc. Although the public is most familiar with pesticide as a means of pest control, the chemical poisons do not constitute the only method. There are five other basic methods of pest control:

1) Legal Methods. These include inspection of animals and plants at county or state lines and ports of entry. Federal seizure and destruction of food contaminated by insect remains would also fall into this category.

2) Mechanical Methods. Mechanical devices such as fly-swatters, house screens, and mouse traps are in this category.

3) Physical Methods. Examples are the use of electric shocks or sound waves, the application of extreme heat, or the flooding of an area to drive out insects.

4) Cultural Methods. This is a broad category including such agricultural techniques as the periodic rotation of crops to reduce disease organisms in the soil, planting a crop after the adult population of a pest has emerged and died, planting a "trap crop" to attract insects away from the desired crop, and breeding strains of animals resistant to the pest.

5) Biological Methods. Strictly speaking, biological control refers to controlling a pest by means of its natural enemies, whether these enemies are predators, parasites or disease-producing organisms. A predator from another locality may be introduced into an area, or the population of a resident predator increased by releasing a number of the predators or making the environment more favorable for them. These techniques have been used with great success in many cases: as early as 1888, the entomologist Albert Koebele introduced the Vedalia beetle from Australia to prey on the cottony cushion scale, which was destroying the citrus industry in California. The success of this first attempt led other states as well as over sixty other countries to eventually implement their own programs of biological control.

The use of a bacteria or virus to control a pest population is a relatively new technique; to date, only a few of these pathogens have been isolated and marketed. One example is milky disease caused by the bacteria, *Bacillus thuringiensis*, which is used to control Japanese beetles.

One of the most promising innovations in the area of biological controls is the use of sterile males to control or eliminate a pest population. This method, developed by Dr. E. F. Knipling of the United States Department of Agriculture, involves rearing large numbers of insect pests, sterilizing the males with high-energy radiation, and releasing the sterile males in an infested area to mate with wild females. The first full-scale test of the method, the application of the sterile male technique to the problem of the screw-worm fly in the southeastern United States, was a spectacular success; it completely eliminated the screw-worm fly population in that area within a matter of months. (See Knipling's article for full details about the sterility method and the eradication program which took place in Florida and surrounding areas.) Research is now in progress to develop and perfect the sterility method for other insect pests, including the oriental fruit fly, the mosquito, the tsetse fly, the boll weevil, and the codling moth. Researchers are also trying to develop effective chemical sterilants; by combining such sterilants with an appropriate bait, the insects already in the area could be sterilized, eliminating the need -- and therefore the difficulties -- of rearing, sterilizing, and then releasing additional insects.

In theory, the application of the sterility principle to higher animals should be just as effective in controlling their populations.

There are many other methods of biological control under research at the present time. Among the new possibilities are the use of a sex attractant combined with a poison; releasing males that will produce sterile offspring; and the transplanting of genes for pesticide resistance into a natural predator of the pest population.

There is a growing movement toward integrated control - the use of an appropriate combination of methods to achieve control over a pest population. The guiding principle behind any integrated program of control is to make the best possible use of all methods of pest control in a coordinated program that deals with the ecosystem as a whole.

PESTICIDES

A pesticide is broadly defined as any substance intended to destroy, prevent, repel, attract, or mitigate the effects of any pests, including insects, rodents, nematodes, fungi, or weeds. It includes plant regulators, defoliants, and desiccants. The following chart lists the primary pesticides and their purposes:

Pesticide	For the Control of
Insecticides	insects (beetles, caterpillars, flies, cockroaches, spiders, mites, etc.) Also include insect repellents and attractants, activators and mothproofers.
Invertebrate animal poisons and repellents	jellyfish, shipworms, barnacles and mollusks, snails and slugs.
Rodenticides	rats, mice, moles
Fungicides	mildews, molds, slime
Nematocides	eelworms
Herbicides	weeds

Defoliants are a class of pesticides used to remove foliage from plants. Desiccants are artificial drying agents. Fumigants, e.g., mothballs, are volatile compounds producing vapors harmful to specific pests.

Insecticides

Prior to World War II, the majority of insecticides in use were stomach poisons which had to be eaten by the insects in order to cause death. With the development of the organic chemicals industry during the war, powerful organic insecticides that killed on contact were synthesized. These poisons were effective for a broad spectrum of insects, and by the late 1940's, the new contact poisons had largely replaced the stomach poisons used before the war.

Throughout the next decade, there was an unrestrained usage of synthetic organic insecticides, a peak occurring in the late '50's. Although there were isolated reports about the immunity that certain insects were gaining to specific insecticides and the fears of a handful of public officials and conservationists about the ecological imbalances caused by the use of pesticides, public concern over their indiscriminate use was only awakened by the publication of Rachel Carson's _SILENT SPRING_ in September of 1962.

Public concern has since moved from the questioning of the benefits and harmful effects of pesticides, to requests for firmer regulation of their use, to outright demands for a complete or partial ban on many pesticides.

Despite the use of astronomical amounts of the synthetic organic pesticides in recent years (as much as 800 million pounds per year in the U. S. alone), it is the belief of many experts in pest control that the insects are getting the upper hand, while we endanger non-target species and cause grave disruption in the ecosystem. Carl B. Huffaker, the Director of the International Center for Biological Control at the University of California at Berkeley, summarized the situation in these terms:

> "In the old approach each problem was considered in isolation from other problems of crop production and environmental quality. Yet even a simple agro-ecosystem presents a maze of interacting loops between pests; between a pest and its natural enemies; and between each of these and cultural practices, weather, soil conditions, plant variety, surrounding fauna and flora, and each organism's capacity to adapt to changed conditions. Moreover, mineral excesses may lead to eutrophication of our inland waters and soil sterility for some crops. All these factors must be viewed as an interlocking system. It is not surprising, then, that the single purpose use of highly toxic synthetic acaricides and insecticides led to severe side effects, including quick resurgence of the pests due to destruction of their natural enemies; development of resistance to the pesticides by target species; hazards to workers in the crops, and to consumers; rise of previously innocuous species to pest status, following the removal of their natural enemies, and a consequent population explosion; and adverse effects not only on the natural enemies but on many valuable nontarget organisms and on man himself, even at great distances from the places treated."*

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*Huffaker, C., _BIOLOGICAL CONTROL AND A REMODELED PEST CONTROL TECHNOLOGY_.

Insecticides can be classified by the way they act on the insect; there are four main categories: stomach poisons, contact poisons, fumigants and desiccants. The HEW manual on insecticides distinguishes each category in the following manner:

> "Stomach poisons must be swallowed to cause death. Contact poisons penetrate the body wall, frequently through the tarsi, as the insect rests on a surface covered with a residual insecticide. Fumigants are volatile chemicals whose vapors enter the insect through the breathing pores, known as spiracles, and the body surfaces. Desiccants are dusts which scratch, abrade, or absorb the fatty, water-resistant outer layer on the insect exoskeleton, causing the insect to lose body fluids and die by dehydration."*

The divisions are not mutually exclusive, since many insecticides act in more than one of the above ways.

The contact insecticides can be broadly classified as organic or inorganic. While some of the organic insecticides are composed of natural organic materials, the majority are synthesized in the laboratory. It is this group of synthetic organic insecticides which is most widely used today.

Within the group of synthetic organic insecticides, two families of compounds compose the majority of the group: the chlorinated hydrocarbons, and the organophosphates.

Chlorinated Hydrocarbons

The chlorinated hydrocarbons include DDT, BHC (benzene hexachloride), dieldrin, aldrin, chlordane and lindane, among others. Although it is not known precisely how these compounds cause death, we do know that they act on the central nervous system. The chlorinated hydrocarbons are selectively soluble in the fats and fatty tissue of organisms and they have great stability as compounds. Their chemical stability makes them effective on a long-term basis and thus especially valuable as residual pesticides. On the other hand, the fact that they do not break down easily means that these chemicals can become concentrated in dangerous amounts in the tissues of organisms as the non-biodegradable chemicals move progressively up the food chain.

Because these compounds are readily absorbed through the insect cuticle, but less easily taken in through mammalian skin, the chlorinated hydrocarbons are far less toxic to mammals dermally.

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*Pratt and Littig, _INSECTICIDES FOR THE CONTROL OF INSECTS OF PUBLIC HEALTH IMPORTANCE_.

A Word on DDT

DDT (Dichloro - Diphenyl - Trichloride) is the most widely used of all insecticides as well as the most studied. Its potential as an insecticide was discovered by Paul Muller in 1939. (Dr. Muller was awarded the Nobel Prize in Medicine in 1949 for his role in the discovery.) Today the majority of the DDT manufactured in the United States is used in the worldwide malaria eradication program. For this purpose, DDT is still the most effective insecticide, and by far the cheapest.

Numerous reports of the hazards of DDT to man and wildlife have led to legislation banning DDT. There are fears that DDT is a carcinogenic agent and that it can cause a degeneration of the liver. But after over 20 years of research, there is still no conclusive evidence that DDT is harmful to human beings unless swallowed in massive doses.

There is evidence, however, against DDT in the case of wildlife. That DDT can accumulate in lethal concentrations in certain species through the process of biologic magnification is well known. It is also well known that fish are especially susceptible to DDT. In more recent research (Porter and Wiemeyer, 1969), it was found that DDT in combination with dieldrin can cause certain hawks and ducks to produce eggs with abnormally thin shells. These documented dangers alone constitute a valid case for limiting the use of DDT or any other non-biodegradable chemical wherever possible.

Organophosphates

The organophosphates include parathion, phosdrin, TEPP, diazinon, azodrin, malathion, and ronnel; like the chlorinated hydrocarbons, they run the gamut from slightly to highly toxic. All the organophosphates work by interfering with the normal mechanism of nerve impulse transmission. They inhibit the enzyme cholinesterase, which normally breaks down the "nerve transmitter substance," acetylocholine. When acetylcholine is allowed to accumulate, uncoordinated activity takes place throughout the animal leading to tremors, convulsions, paralysis, and finally death. Some of the organophosphates inhibit other enzymes besides cholinesterase.

Unlike the chlorinated hydrocarbons, the organophosphates are short-term, breaking down easily, and do not in general accumulate in the ecosystem.

THE STERILE-MALE TECHNIQUE

Over 30 years ago Dr. Edward Knipling, today science adviser to the U. S. Department of Agriculture's Entomology Research Branch, first proposed a unique method of pest control: the control of an insect population through the release of sterile males. The idea was met with a good deal of skepticism at the time of its proposal, but Dr. Knipling persisted in his research. His target was the screw-worm fly, a major insect enemy of livestock in the South. The females of the species lay their eggs in the open wounds of animals, and the hatching larvae feed on the flesh. Unless treated, even full-grown animals die in a matter of days. Annual losses of livestock due to the screw-worm fly in the United States alone have been estimated at $40 million; the toll in wildlife is not known.

In 1950 Knipling received the assistance of R. C. Bushland and his staff at the USDA station in Kerville, Texas, in developing a way of sterilizing male screw-worm flies that would not produce other adverse effects on the insects. The success of this effort cleared the way for the first field tests of the method.

These tests were conducted on Sanibel Island, a small island two miles off the west coast of Florida, and on the island of Curacao in the Netherlands Antilles. The success of both ventures resulted in demands from the Florida livestock industry for a similar program to eradicate the screw-worm fly in their region. In 1957 such a program was jointly undertaken by the Department of Agriculture and the Florida Livestock Board for Florida and sections of Georgia and Alabama. Sterile fly releases were started in January of 1958; by February of the following year, it appeared that the screw-worm fly had been eliminated from the southeastern United States. (See Knipling's article for full details about the Florida program, as well as the procedure for rearing and sterilizing the flies.)

Advance of the Sterile Male Technique

The success of these initial attempts to implement the sterility principle completely verified Knipling's theoretical calculations for the effectiveness of the method over the use of a conventional pesticide in the case of the screw-worm fly. Moreover, the sterile male technique has the advantage of becoming increasingly more effective as the pest population declines -- unlike pesticide applications that kill fewer and fewer insects with subsequent applications.

Other advantages of the sterile male technique are that it affects only the pest population, leaving other species undisturbed, and insects cannot become resistant to it as they can to a pesticide. However, the sterile male technique cannot be used effectively against every insect pest, and it can only be used under certain conditions. Moreover, the technique is often most effective in conjunction with other methods of control, including pesticides. Before any attempt is made to implement a sterility program, the answers to the following questions must be considered:

1) Can males of the pest species be sterilized without seriously affecting their mating competitiveness? (This is the primary problem holding up the control of the boll weevil by the sterility principle.)

2) Is there a practical way to rear or collect the quantity of insects, perhaps in the tens or hundreds of million per week, necessary for the program? Will these laboratory reared insects be able to adapt to the natural environment when released?

3) Is the density of the pest population in the area low enough to require the release of a manageable number of insects? If not, can the population be reduced (by a pesticide or other means) to a level that could be handled by the sterile male technique?

4) Will the release of such large numbers of sterile insects cause damage or injury to crops, livestock, property, etc. even temporarily, which would outweigh the benefits of eventually having the pest under control? (For example, temporary increase of a few million houseflies in an area might prove objectionable and a health hazard to residents.)

5) In terms of the economics of pest control: Is the cost for rearing and releasing the required number of sterile males for a particular species competitive with the current cost of other means of pest control? If the cost is greater, can the greater cost be justified in terms of savings or benefits in other areas, e.g., environmental safety or more effective control?

It is evident that the success of any sterility program requires extensive knowledge about the life cycle and habits of a pest population, as well as knowledge about the place of that pest in the ecosystem. We must know the population densities of the insect at different times of the year in order to determine when sterile males should be released and the number of them required to cause a downward trend in the population. We must know their mating and migratory habits. Over what range can the pest travel? Is there danger of an area where the pest has been seemingly eliminated being re-infested by immigrating insects?

Lack of information or misinformation about any crucial factor may lead to the failure of a sterility program.

The Sterility Principle in Integrated Control

The strength of the sterility method is that it becomes increasingly more efficient as the number of insects declines -- in direct contrast to pesticide applications, where the use of the same amount of pesticide in an area kills fewer and fewer insects as the population declines. Thus an integrated program using some method to significantly reduce the initial pest population, combined with the subsequent release of sterile males, would be highly effective -- quicker and more effective than the use of either method alone.

There are many possibilities being explored for using sterile male releases in conjunction with other methods of control, and these methods are not limited to pesticides. A high initial population can also be reduced by first releasing parasites or predators of the pest. The use of male sex lures in combination with a poison would likewise reduce the male population and lower the number of sterile males required. Ultimately, the most effective application of the sterility principle will not involve the release of additional numbers of sterile males, but the sterilization of males (or females) already in the area. This will be possible with the development of effective chemical sterilants (chemosterilants).

II. THE *STERL* MODEL

ASSUMPTIONS

1) The maximum capacity of the area is 1 million male flies.

2) Adult flies (both steriles and normals) live a total of 17 days as adults.

3) Initially, there are no sterile males and the initial population of 1 million normal males is distributed equally over each of the 17 days of adult life.

4) There are equal numbers of normal males and females in the population at all times.

5) When the total adult male population in the area is less than 1 million, immigration of adult flies from outside the area will occur.

6) The number of flies immigrating into the area is equal to one tenth of the difference between the actual number of flies in the area and the maximum capacity of 1 million.

7) The immigrating flies are equally distributed over all ages.

8) When the male fly population is greater than 1 million, there is a pressure to disperse out of the area in proportion to the distribution of normal:sterile males.

9) All males in excess of 1 million emigrate.

10) When flies emigrate, equal numbers leave from each age group.

11) All adult male flies mate with females three days after emergence from the pupal state.

12) Female flies deposit eggs 7 days after reaching adulthood.

13) Each fertilized adult female is capable of depositing 250 eggs. However, only a small percentage of these eggs reach adulthood. This percentage is given by a linear equation that is specified by a 1% survival rate when the normal adult male population is 1 million and a 4% survival rate when this population is 100,000.

14) Adult flies emerge 13 days after the eggs are laid.

15) The pesticide is effective only on the day of application. There is no residual effect.

16) Application of pesticide eliminates 90% of the adult fly population. Normal and sterile males are affected equally.

17) The mating efficiency of sterile males is only 25%; that is, four sterile adult male flies are needed to effectively compete with one fertile male fly. The reason is that the irradiation which sterilizes these males weakens many of them physically, and diminishes their sex drive.

18) The cost factors are based on the following data:

   a) Estimated damage to cattle

      i) 10% of the fertile females will mate and be able to deposit their eggs in the face of cattle.

      ii) Ten females depositing their eggs in the face of one cow will result in death to the cow. It therefore takes 100 fertile female flies to kill one cow/month.

      iii) Death of cattle results in a \$200 loss per animal. This results in damage costs of 1/15 (\$1.00)/fly/day.

   b) Fly control program

      i) Pesticides - \$100,000/application or \$10/square mile.

      ii) 1¢/fly to raise and release.

Definition of Variables

D = natural deaths of normal males

D1 = natural deaths of sterile males

P_1 = newly emerged normal adult males

P_i = normal adult males i days old

Q_i = sterile males i days old

E_1 = newly laid male eggs

E_i = male eggs laid i days ago

C = per cent of fertilized eggs that reach adulthood

C9 = cost of control program in thousands of dollars

Pop_T = total population of day T

X = total number of normal adult male flies on day T-1

X1 = total number of normal adult male flies on day T

S = total number of normal adult male flies over 75 days
(i.e. S/15 = est. dollar damage)

S_T = total sterile males on day T = $\sum_{i=1}^{17} Q_i$

X9 = maximum number of flies area can support = 10^6

Z = number of excess flies

F1 = fraction of adult males leaving area, if there is emigration

F2 = fraction of adult males destroyed by pesticide = 0.9

F3 = fraction of eggs which are fertilized

BO = number of male eggs laid per adult female = 125

V_i = number of normal males i days ago

W_i = number of sterile males i days ago

NOTE: The arithmetic in the computer is done slightly differently, with different notation. Refer to program listing for details.

EQUATIONS

NOTE: All subscripts refer to the age of the group -- e.g., P_7 = number of seven-day-old normal males.

The equations below are arranged in the order in which they are processed.

death of old flies:

$$D = P_{17} \tag{1}$$

$$D1 = Q_{17} \tag{2}$$

emergence of normal adult males:

$$P_1 = C * E_{13} \tag{3a}$$

$$C = -3.33E-8 * X + .04333 \tag{3b}$$

total flies in area on any day T:

$$Pop_T = X + S_T + S_T + P_1 - D - D1 \tag{4}$$

excess flies:

$$Z = Pop_T - X9 \tag{5}$$

If $Z < 0$, then there is immigration;
otherwise, there is emigration.

immigration:

$$(Z < 0) \text{ immigrating adult males} = 0.1 * Z; \tag{6}$$

$$\text{for all ages } i,\ P_i = P_i + \frac{0.1 * Z}{17} \tag{7}$$

emigration:

$(Z \geq 0)$ fraction leaving = F1

$$F1 = \frac{\text{no. of excess flies}}{\text{total no. flies}}$$

$$F1 = \frac{Z}{Pop_T} \tag{8}$$

Number of male flies, for ages i:

$$P_i = (1 - F1) * P_i \tag{9}$$

$$Q_i = (1 - F1) * Q_i \tag{10}$$

pesticide effect:

$$F2 = 0.9 \tag{11}$$

For each age group i:

$$P_i = (1 - F2) * P_i \tag{12}$$

$$Q_i = (1 - F2) * Q_i \tag{13}$$

sterile male effect:

$$F3 = \frac{V_4}{V_4 + 0.25 * W_4} \tag{14}$$

no. of eggs produced:

$$E_1 = B0 * P_7 * F3 \tag{15}$$

NOTE: TEACHERS WISHING TO USE THE STERL PROGRAM WITHOUT A COST FACTOR CAN DO SO BY DELETING LINES 1180 THROUGH 1240.

III. PROGRAM LISTING

```
100 REM STERL  -- PROGRAM ON FLY POPULATION CONTROL BY INTRODUCTION
105 REM OF STERILE MALE FLIES AND USE OF PESTICIDE
110 REM COPYRIGHT 1972 - STATE UNIVERSITY OF NEW YORK
115 REM S(T)=NUMBER OF STERILE MALES ON DAY T
120 REM INFORMATION ON THE LIFE CYCLE OF THE FLY IS CONTAINED IN THE
125 REM E,P,Q,V, AND W ARRAYS, WHICH ARE TREATED AS CIRCULAR QUEUES.
130 REM E=EGGS, G=POINTER FOR E
135 REM P=NORMAL MALES, Q=STERILE MALES, L=POINTER FOR P AND Q
140 REM V=POPULATION OF NORMAL MALES FOUR DAYS AGO
145 REM W=POPULATION OF STERILE MALES FOUR DAYS AGO
150 REM P1=POINTER FOR V AND W
155 REM PROGRAM DEVELOPED BY L. BRAUN AND A. FRISHMAN
160 REM PROGRAMMED BY C. LOSIK, JANUARY 1971
165 REM MODIFIED BY L. KAUFMAN, JUNE 1972
170 REM LATEST REVISION: 8-28-72
175 PRINT " ","CONTROL OF SCREW-WORM FLY POPULATION"
180 PRINT
185 PRINT "INSTRUCTIONS (1=YES, 0=NO)";
190 INPUT F
195 IF F=0 THEN 330
200 IF F<>1THEN185
205 PRINT
210 PRINT "YOUR GOAL WILL BE TO ELIMINATE THE ONE MILLION MALE"
215 PRINT "FLIES NOW IN YOUR 10000 SQUARE MILE AREA, THUS DESTROYING"
220 PRINT "THE TOTAL FLY POPULATION.  YOU MAY USE A PESTICIDE,"
225 PRINT "RELEASE STERILE MALE FLIES, OR BOTH.  INDICATE THE TYPE"
230 PRINT "OF CONTROL PROGRAM YOU WANT BY TYPING IN THE APPROPRIATE"
235 PRINT "RESPONSES TO THE FOLLOWING QUESTIONS:"
240 PRINT
245 PRINT "'PESTICIDE?'"
250 PRINT "  0= NO PESTICIDES."
255 PRINT "  1= PESTICIDES ON SPECIFIED DAYS.  INDICATE"
260 PRINT "     THESE DAYS BY TYPING A DAY NUMBER (BETWEEN 1 AND 75)"
265 PRINT "     NEXT TO EACH '?' THAT APPEARS; TYPE 0 WHEN FINISHED."
270 PRINT
275 PRINT "'STERILE FLIES?'"
280 PRINT "  0= NO STERILE FLIES."
285 PRINT "  1= STERILE FLIES WILL BE RELEASED.  COMPUTER WILL"
290 PRINT "     ASK 'HOW OFTEN?'  TYPE 1=DAILY OR 2=CERTAIN DAYS"
295 PRINT "  IF 1, SPECIFY NUMBER OF FLIES EACH DAY (UP TO 1000000),"
300 PRINT "        THE FIRST DAY OF THE PERIOD, AND THE LAST DAY"
305 PRINT "        (BETWEEN 1 AND 75 DAYS)."
310 PRINT "  IF 2, FOR EACH DAY SELECTED, SPECIFY THE DAY NUMBER"
315 PRINT "       (BETWEEN 1 AND 75) AND THE NUMBER OF STERILE FLIES"
320 PRINT "        (UP TO 1000000).  USE A NEW LINE FOR EACH DAY."
325 PRINT "        TYPE 0,0 WHEN FINISHED."
330 PRINT
```

```
335 PRINT "**********"
340 REM SET UP INITIAL CONDITIONS
345 DIM S(76),P(17),Q(17),E(13),V(4),W(4)
350 REM T1:DAYS FROM EGG TO ADULT
355 LET T1=13
360 REM T2:LIFE SPAN AS ADULT
365 LET T2=17
370 REM X9:MAXIMUM NUMBER OF MALE FLIES THAT THE AREA CAN SUPPORT
375 LET X9=1000000
380 REM K:SEXUAL EFFECTIVENESS COEFFICIENT OF STERILE MALES
385 LET K=.25
390 REM B0:NORMAL BIRTH RATE OF MALES
395 LET B0=250/2
400 REM C:SURVIVAL RATE OF EGG,MAGGOT,PUPA
405 LET C=.01
410 REM C9:COST OF CONTROL PROGRAM IN THOUSANDS OF DOLLARS
415 LET C9=0
420 REM S:TOTAL NUMBER OF NORMAL FLIES
425 LET S=0
430 REM START POPULATION AT MAXIMUM VALUE
435 LET X=X9
440 LET S(1)=0
445 REM INITIAL CONDITIONS FOR ADULT MALES AND EGGS
450 FOR L=1 TO T2
455 LET P(L)=X/T2
460 LET Q(L)=0
465 NEXT L
470 FOR G=1TOT1
475 LET E(G)=B0*X/T2
480 NEXT G
485 FOR P1=1 TO 4
490 LET V(P1)=X/T2
495 LET W(P1)=0
500 NEXT P1
505 LET L=17
510 LET G=13
515 LET P1=4
520 FOR T=2 TO 76
525 LET S(T)=1
530 NEXT T
535 PRINT
540 REM DETERMINE OPTIONS IN MODEL
545 PRINT "PESTICIDE (1=YES, 0=NO)";
550 INPUT T
555 IF T=0 THEN 605
560 IF T<>1THEN545
565 PRINT "WHICH DAYS"
570 INPUT T
575 IF T=0 THEN 605
580 IF ABS(T-38)>37 THEN 565
585 IF T<>INT(T)THEN565
590 LET S(T+1)=-1
595 LET C9=C9+100
```

```
600 GOTO 570
605 PRINT
610 PRINT "STERILE FLIES (1=YES, 0=NO)";
615 INPUT T
620 IF T=0 THEN 775
625 IF T<>1THEN605
630 PRINT "HOW OFTEN (1=DAILY, 2=SELECTED DAYS)";
635 INPUT T
640 IF T=1 THEN 700
645 IF T<>2THEN630
650 PRINT "DAY, NUMBER OF FLIES"
655 INPUT T,J
660 IF T=0 THEN 775
665 IF ABS(J-X9/2)>X9/2 THEN 650
670 IF J<>INT(J)THEN650
675 IF ABS(T-38)>37THEN650
680 IF T<>INT(T)THEN650
685 LET S(T+1)=S(T+1)*J
690 LET C9=C9+1E-5*J
695 GOTO 655
700 PRINT "HOW MANY PER DAY";
705 INPUT J
710 IF ABS(J-X9/2)>X9/2 THEN 700
715 IF J<>INT(J)THEN700
720 PRINT "FROM WHEN, TO WHEN";
725 INPUT T,T9
730 IF ABS(T9-38)>37THEN720
735 IF T9<>INT(T9)THEN720
740 IF ABS(T-38)>37THEN720
745 IF T<>INT(T)THEN720
750 IF T>T9 THEN 720
755 FOR F=T+1 TO T9+1
760 LET S(F)=S(F)*J
765 NEXT F
770 LET C9=C9+J*(T9-T+1)*1E-5
775 PRINT
780 PRINT " ","MILLIONS OF NORMAL ADULT MALE FLIES"
785 PRINT "     0         .2        .4        .6        .8        1"
790 PRINT "DAY  I---------I---------I---------I---------I---------I"
795 PRINT 0;TAB(4);"I";TAB(55);"* ";INT(X+.5)
800 REM START SIMULATION
805 FOR T=1 TO 75
810 REM OLD AGE DEATHS IN POPULATION
815 LET D=P(L)
820 LET D1=Q(L)
```

```
825 REM BIRTHS IN POPULATION
830 LET T9=T+1
835 LET C=-3.33E-08*X+.04333
840 LET P(L)=C*E(G)
845 IF S(T9)=-1THEN855
850 IF S(T9)<>1 THEN865
855 LET Q(L)=0
860 GOTO870
865 LET Q(L)=ABS(S(T9))
870 IF S(T)=-1THEN885
875 REM EMIGRATION/IMMIGRATION EFFECTS
880 IF S(T)<>1THEN890
885 LET S(T)=0
890 LET Z=X+P(L)+ABS(S(T))-(D+D1+X9)
895 IF Z<0 THEN 915
900 LET F=Z/(Z+X9)
905 GOSUB 1125
910 GOTO 945
915 LET D=D+.1*Z
920 LET Z=ABS(.1*Z/T2)
925 FOR J=1 TO T2
930 LET P(J)=P(J)+Z
935 NEXT J
940 REM PESTICIDE EFFECTS
945 IF S(T9)>=0THEN960
950 LET F=.9
955 GOSUB 1125
960 LET X1=X+C*E(G)-D
965 IF S(T9)=-1THEN975
970 IF S(T9)<>1THEN980
975 LET S(T9)=0
980 LET S(T9)=ABS(S(T))+ABS(S(T9))-D1
985 LET S=S+INT(X1+.5)
990 PRINT T;TAB(4);"I";TAB(5+INT(50*X1/X9+.5));"* ";INT(X1+.5)
995 REM BACK UP SEVEN DAYS FOR EGG CALCULATION
1000 LET Z=L-7
1005 IF Z>=1THEN1015
1010 LET Z=Z+T2
1015 LET F=V(P1)+K*W(P1)
1020 IF F>.5 THEN 1035
1025 LET E(G)=P(Z)*B0
1030 GOTO 1040
```

```
1035 LET E(G)=P(Z)*B0*V(P1)/F
1040 LET Z=L-3
1045 IF Z>=1THEN1055
1050 LET Z=Z+T2
1055 LET V(P1)=P(Z)
1060 LET W(P1)=Q(Z)
1065 LET L=L+1
1070 IF L<=T2THEN1080
1075 LET L=1
1080 LET G=G+1
1085 IF G<=T1THEN1095
1090 LET G=1
1095 LET P1=P1+1
1100 IF P1<=4THEN1110
1105 LET P1=1
1110 LET X=X1
1115 NEXT T
1120 GOTO 1165
1125 LET Z=1-F
1130 FOR J=1 TO T2
1135 LET D=D+F*P(J)
1140 LET D1=D1+F*Q(J)
1145 LET P(J)=Z*P(J)
1150 LET Q(J)=Z*Q(J)
1155 NEXT J
1160 RETURN
1165 PRINT "     I---------I---------I---------I---------I---------I"
1170 PRINT
1175 PRINT
1180 PRINT "COST OF FLY CONTROL: $";
1185 IF C9>=1000THEN1200
1190 PRINT C9;" THOUSAND";
1195 GOTO1205
1200 PRINT C9/1000;" MILLION";
1205 PRINT" DOLLARS"
1210 PRINT
1215 PRINT"ESTIMATED DAMAGE: $";
1220 IF S/15000>=1000THEN1235
1225 PRINT S/15000;" THOUSAND";
1230 GOTO1240
1235 PRINT S/(15*1E6);" MILLION";
1240 PRINT" DOLLARS"
1245 PRINT
1250 PRINT "ANOTHER RUN (1=YES, 0=NO)";
1255 INPUT T
1260 IF T=1 THEN 330
1265 IF T<>0THEN1250
1270 END
```

IV. ADDITIONAL SAMPLE RUNS

RUN 1 - A pesticide is applied every seven days, but no sterile males are released. The behavior is cyclic with a period of seven days: after each application of pesticide, the population is drastically reduced, then begins to rise again.

RUN 2 - Pesticide is applied every day for the first 24 days, with no release of sterile males. As soon as control measures are lifted on day 25, the population begins to rise and soon returns to the carrying capacity of one million.

RUN 3 - This run demonstrates the effects of releasing an insufficient number of sterile flies. The dips at days 21, 41, and 61 reflect the initial reduction of the population by an application of pesticide on day 1. The 20-day lag results from a 20-day period from the laying of eggs to the maturation of the new females and their laying of eggs.

RUN 4 - 100,000 sterile flies are released for the first 24 days with a resultant downward trend in the population. With no more sterile fly releases, the population begins to increase, at first slowly, then more rapidly as the remaining sterile flies die off.

RUN 5 - This is an integrated control program with pesticide applied every seven days and 100,000 sterile males released every day. But the program is ineffective because the periodic application of pesticide kills both normal and sterile flies.

RUN 1

```
**********

PESTICIDE (1=YES, 0=N0)? 1
WHICH DAYS
? 1
? 8
? 15
? 22
? 29
? 36
? 43
? 50
? 57
? 64
? 71
? 0

STERILE FLIES (1=YES, 0=NO)? 1
HOW OFTEN (1=DAILY, 2=SELECTED DAYS)? 1
HOW MANY PER DAY? 100000
FROM WHEN, TO WHEN? 2,75

              MILLIONS OF NORMAL ADULT MALE FLIES
     0        .2        .4        .6        .8         1
DAY  I---------I---------I---------I---------I---------I
 0  I                                                  *  1.000000E+6
 1  I     *  100000
 2  I                      *  449490
 3  I                                  *  673776
 4  I                                        *  803252
 5  I                                      *  756018
 6  I                                    *  729439
 7  I                                   *  709264
 8  I   *  69455
 9  I                     *  429629
 10 I                                 *  661288
 11 I                                       *  772944
 12 I                                     *  735809
 13 I                                    *  715376
 14 I                                 *  664364
 15 I   *  61634
 16 I          *  200975
 17 I               *  305555
 18 I                   *  375353
 19 I                     *  417780
 20 I                      *  439335
 21 I                      *  430078
 22 I  *  42266
 23 I          *  190571
 24 I              *  289349
 25 I                  *  350572
 26 I                    *  391476
 27 I                     *  417940
 28 I                    *  408543
 29 I  *  41195
 30 I           *  212814
 31 I                 *  336928
 32 I                     *  427671
 33 I                         *  503828
 34 I                           *  531507
 35 I                        *  480664
 36 I  *  44881
 37 I         *  177454
 38 I              *  276384
 39 I                 *  345889
 40 I                    *  405028
 41 I                      *  442022
 42 I                      *  433275
 43 I  *  40574
 44 I        *  169015
 45 I             *  260905
 46 I                *  327536
 47 I                   *  383469
 48 I                     *  412688
 49 I                    *  405066
 50 I  *  39270
 51 I         *  182565
 52 I               *  293637
 53 I                   *  381713
 54 I                      *  441173
 55 I                        *  473706
 56 I                      *  449973
 57 I  *  41754
 58 I         *  171915
 59 I              *  271712
 60 I                  *  352958
 61 I                     *  418891
 62 I                       *  456211
 63 I                      *  441568
 64 I  *  40824
 65 I        *  165918
 66 I             *  262546
 67 I                 *  340117
 68 I                    *  399905
 69 I                      *  433383
 70 I                     *  423802
 71 I  *  39817
 72 I         *  176641
 73 I              *  286611
 74 I                  *  366236
 75 I                     *  427530
     I---------I---------I---------I---------I---------I

 COST OF FLY CONTROL: $ 1.174  MILLION DOLLARS

 ESTIMATED DAMAGE: $ 1.802047  MILLION DOLLARS

 ANOTHER RUN (1=YES, 0=NO)? 0
```

RUN 2

```
**********

PESTICIDE (1=YES, 0=NO)? 1
WHICH DAYS
? 1
? 2
? 3
? 4
? 5
? 6
? 7
? 8
? 9
? 10
? 11
? 12
? 13
? 14
? 15
? 16
? 17
? 18
? 19
? 20
? 21
? 22
? 23
? 24
? 0

STERILE FLIES (1=YES, 0=NO)? 0

              MILLIONS OF NORMAL ADULT MALE FLIES
     0        .2        .4        .6        .8         1
DAY  I---------I---------I---------I---------I---------I
 0 I                                                  *  1.000000E+6
 1 I     *  100000
 2 I  *  44949
 3 I  *  41645
 4 I  *  41462
 5 I  *  41454
 6 I  *  41453
 7 I  *  41453
 8 I  *  41453
 9 I  *  41453
10 I  *  41453
11 I  *  41454
12 I  *  41454
13 I  *  41454
14 I *  16428
15 I *  11878
16 I *  11242
17 I *  11162
18 I *  11152
19 I *  11151
20 I *  11151
21 I *  11151
22 I *  11151
23 I *  11151
24 I *  11151
25 I      *  111510
26 I          *  196447
27 I             *  268705
28 I                *  329455
29 I                   *  380072
30 I                     *  421864
31 I                       *  455976
32 I                        *  483393
33 I                         *  504964
34 I                          *  521414
35 I                           *  533364
36 I                           *  541345
37 I                           *  545811
38 I                            *  563581
39 I                              *  591089
40 I                               *  624936
41 I                                 *  662073
42 I                                   *  698984
43 I                                     *  740932
44 I                                       *  784606
45 I                                          *  831012
46 I                                           *  864519
47 I                                             *  890820
48 I                                              *  911471
49 I                                              *  928193
50 I                                               *  942365
51 I                                                *  954833
52 I                                                *  966094
53 I                                                 *  976429
54 I                                                 *  985999
55 I                                                 *  978480
56 I                                                *  959046
57 I                                               *  931738
58 I                                              *  924701
59 I                                               *  933374
60 I                                                *  950733
61 I                                                 *  971042
62 I                                                 *  988258
63 I                                                  *  1.000000E+6
64 I                                                  *  1.000000E+6
65 I                                                  *  1.000000E+6
66 I                                                  *  1.000000E+6
67 I                                                  *  1.000000E+6
68 I                                                  *  1.000000E+6
69 I                                                  *  1.000000E+6
70 I                                                  *  1.000000E+6
71 I                                                  *  1.000000E+6
72 I                                                  *  1.000000E+6
73 I                                                  *  1.000000E+6
74 I                                                  *  1.000000E+6
75 I                                                  *  1.000000E+6
     I---------I---------I---------I---------I---------I

COST OF FLY CONTROL: $ 2.4  MILLION DOLLARS

ESTIMATED DAMAGE: $ 2.705302  MILLION DOLLARS

ANOTHER RUN (1=YES, 0=NO)? 1
```

RUN 3

```
**********

PESTICIDE (1=YES, 0=N0)? 1
WHICH DAYS
? 1
? 0

STERILE FLIES (1=YES, 0=NO)? 1
HOW OFTEN (1=DAILY, 2=SELECTED DAYS)? 1
HOW MANY PER DAY? 10000
FROM WHEN, TO WHEN? 2,75

              MILLIONS OF NORMAL ADULT MALE FLIES
     0        .2        .4        .6        .8         1
DAY  I---------I---------I---------I---------I---------I
 0  I                                                  *  1.000000E+6
 1  I     *  100000
 2  I                      *  449490
 3  I                                  *  682776
 4  I                                          *  838517
 5  I                                               *  942532
 6  I                                                *  962187
 7  I                                                *  956261
 8  I                                                *  951059
 9  I                                               *  946374
 10 I                                               *  942175
 11 I                                               *  938425
 12 I                                               *  935090
 13 I                                               *  932133
 14 I                                              *  923844
 15 I                                              *  915487
 16 I                                             *  907668
 17 I                                             *  900244
 18 I                                             *  893019
 19 I                                       *  780710
 20 I                                    *  720236
 21 I                                   *  693107
 22 I                                             *  903776
 23 I                                              *  917029
 24 I                                              *  921911
 25 I                                              *  922281
 26 I                                              *  920049
 27 I                                              *  917650
 28 I                                              *  915844
 29 I                                              *  914671
 30 I                                              *  914122
 31 I                                              *  916465
 32 I                                              *  919241
 33 I                                              *  922349
 34 I                                              *  917269
 35 I                                              *  911732
 36 I                                             *  906447
 37 I                                             *  901176
 38 I                                             *  895882
 39 I                                       *  775666
 40 I                                     *  731984
 41 I                                    *  711641
 42 I                                             *  905655
 43 I                                              *  916774
 44 I                                              *  920832
 45 I                                              *  920702
 46 I                                              *  917812
 47 I                                              *  914819
 48 I                                              *  912478
 49 I                                              *  910786
 50 I                                             *  909739
 51 I                                              *  913040
 52 I                                              *  917753
 53 I                                              *  923743
 54 I                                              *  919514
 55 I                                              *  914240
 56 I                                             *  908965
 57 I                                             *  903478
 58 I                                             *  897901
 59 I                                       *  772873
 60 I                                     *  740314
 61 I                                    *  725658
 62 I                                              *  910097
 63 I                                              *  919742
 64 I                                              *  923003
 65 I                                              *  922237
 66 I                                              *  918517
 67 I                                              *  914694
 68 I                                              *  911509
 69 I                                             *  908816
 70 I                                             *  906492
 71 I                                              *  910049
 72 I                                              *  916375
 73 I                                              *  925358
 74 I                                              *  922081
 75 I                                              *  916934
     I---------I---------I---------I---------I---------I


COST OF FLY CONTROL: $ 107.4  THOUSAND DOLLARS

ESTIMATED DAMAGE: $ 4.377433  MILLION DOLLARS

ANOTHER RUN (1=YES, 0=NO)? 1
```

RUN 4

```
**********

PESTICIDE (1=YES, 0=NO)? 1
WHICH DAYS
? 1
? 0

STERILE FLIES (1=YES, 0=NO)? 1
HOW OFTEN (1=DAILY, 2=SELECTED DAYS)? 1
HOW MANY PER DAY? 100000
FROM WHEN, TO WHEN? 2,24

              MILLIONS OF NORMAL ADULT MALE FLIES
     0        .2        .4        .6        .8         1
DAY  I---------I---------I---------I---------I---------I
 0  I                                                  *  1.000000E+6
 1  I     *  100000
 2  I                      *  449490
 3  I                                  *  673776
 4  I                                        *  803252
 5  I                                      *  756018
 6  I                                    *  729439
 7  I                                   *  709264
 8  I                                   *  694553
 9  I                                  *  683936
 10 I                                  *  676357
 11 I                                  *  671004
 12 I                                 *  667261
 13 I                                 *  664675
 14 I                               *  619643
 15 I                             *  577473
 16 I                           *  543133
 17 I                          *  513161
 18 I                        *  484279
 19 I                      *  446728
 20 I                     *  413758
 21 I                   *  386458
 22 I                          *  523585
 23 I                            *  564634
 24 I                            *  562284
 25 I                           *  543579
 26 I                             *  573112
 27 I                              *  604246
 28 I                                *  635979
 29 I                                 *  667882
 30 I                                   *  699767
 31 I                                     *  736609
 32 I                                       *  772065
 33 I                                        *  805939
 34 I                                        *  807846
 35 I                                         *  815034
 36 I                                         *  825157
 37 I                                          *  836220
 38 I                                          *  845650
 39 I                                       *  775370
 40 I                                     *  740332
 41 I                                     *  731039
 42 I                                                 *  983860
 43 I                                                  *  1.000000E+6
 44 I                                                  *  1.000000E+6
 45 I                                                 *  987571
 46 I                                                 *  977702
 47 I                                                 *  972075
 48 I                                                *  968887
 49 I                                                *  963864
 50 I                                                *  957105
 51 I                                                  *  1.000000E+6
 52 I                                                  *  1.000000E+6
 53 I                                                  *  1.000000E+6
 54 I                                                  *  1.000000E+6
 55 I                                                  *  1.000000E+6
 56 I                                                  *  1.000000E+6
 57 I                                                  *  1.000000E+6
 58 I                                                  *  1.000000E+6
 59 I                                         *  829444
 60 I                                        *  801219
 61 I                                        *  801620
 62 I                                                  *  1.000000E+6
 63 I                                                  *  1.000000E+6
 64 I                                                  *  1.000000E+6
 65 I                                                  *  1.000000E+6
 66 I                                                  *  1.000000E+6
 67 I                                                  *  1.000000E+6
 68 I                                                  *  1.000000E+6
 69 I                                                  *  1.000000E+6
 70 I                                                  *  1.000000E+6
 71 I                                                  *  1.000000E+6
 72 I                                                  *  1.000000E+6
 73 I                                                  *  1.000000E+6
 74 I                                                  *  1.000000E+6
 75 I                                                  *  1.000000E+6
     I---------I---------I---------I---------I---------I

COST OF FLY CONTROL: $ 123  THOUSAND DOLLARS

ESTIMATED DAMAGE: $ 3.971556  MILLION DOLLARS

ANOTHER RUN (1=YES, 0=NO)? 1
```

RUN 5

```
**********

PESTICIDE (1=YES, 0=NO)? 1
WHICH DAYS
? 1
? 8
? 15
? 22
? 29
? 36
? 43
? 50
? 57
? 64
? 71
? 0

STERILE FLIES (1=YES, 0=NO)? 0

              MILLIONS OF NORMAL ADULT MALE FLIES
     0        .2        .4        .6        .8         1
DAY  I---------I---------I---------I---------I---------I
  0 I                                                  *  1.000000E+6
  1 I     *  100000
  2 I                      *  449490
  3 I                                  *  683776
  4 I                                          *  841144
  5 I                                               *  947162
  6 I                                                  *  1.000000E+6
  7 I                                                  *  1.000000E+6
  8 I     *  100000
  9 I                       *  453701
 10 I                                   *  690874
 11 I                                           *  850247
 12 I                                                *  957680
 13 I                                                  *  1.000000E+6
 14 I                                                  *  999608
 15 I     *  100000
 16 I            *  240883
 17 I                  *  361287
 18 I                       *  461461
 19 I                           *  540636
 20 I                              *  604065
 21 I                               *  628742
 22 I    *  72076
 23 I              *  273307
 24 I                     *  415921
 25 I                          *  519751
 26 I                              *  593328
 27 I                                 *  651571
 28 I                                  *  671340
 29 I    *  76440
 30 I               *  301822
 31 I                       *  467250
 32 I                              *  593491
 33 I                                   *  691829
 34 I                                      *  757564
 35 I                                       *  771356
 36 I    *  80296
 37 I            *  242943
 38 I                   *  384096
 39 I                         *  503653
 40 I                              *  602444
 41 I                                  *  677667
 42 I                                   *  699210
 43 I    *  75285
 44 I            *  248787
 45 I                   *  388531
 46 I                         *  501479
 47 I                              *  593101
 48 I                                 *  661306
 49 I                                  *  683359
 50 I    *  74538
 51 I             *  263925
 52 I                     *  417642
 53 I                           *  542892
 54 I                                *  640113
 55 I                                   *  709611
 56 I                                    *  726924
 57 I    *  76807
 58 I             *  251653
 59 I                    *  402166
 60 I                          *  528362
 61 I                               *  629552
 62 I                                   *  702009
 63 I                                    *  720495
 64 I    *  76488
 65 I            *  249885
 66 I                    *  396002
 67 I                          *  517822
 68 I                               *  614880
 69 I                                  *  685670
 70 I                                   *  705299
 71 I    *  75538
 72 I             *  257063
 73 I                    *  408990
 74 I                           *  532595
 75 I                               *  629808
     I---------I---------I---------I---------I---------I


COST OF FLY CONTROL: $ 1.1  MILLION DOLLARS

ESTIMATED DAMAGE: $ 2.536446  MILLION DOLLARS

ANOTHER RUN (1=YES, 0=NO)? 1
```

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